UCRL-ID-121170

Parametric Fits to 1-D Neutron Transport Calculations for Lithium-Vanadium Fusion Power Plant Blankets in Cylindrical and Spherical Geometries

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June 16, 1995

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Synopsis:

We have performed 1-D coupled, neutron-gamma transport calculations for lithium-vanadium blankets and lithium-sodium cauldron "pot" blankets in cylindrical and spherical geometries. Parametric fits to the data are supplied for subsequent use in systems code models. Scaling relationships are given for various neutronics parameters of interest, including: tritium breeding ratio, neutron energy multiplication, magnet dose rates, magnet heating rates, and integrated magnet fluence.

Introduction:

We are intending to use the SuperCode[1] to optimize the costs of alternate fusion power plant designs, particularly the spheromak. We wanted to calculate and optimize the size and cost of a self cooled lithium vanadium blanket with an appropriate shield for both a field reversed configuration (FRC) power plant and a spheromak power plant. We used the ONEDANT, 1-D coupled neutron-gamma transport code to calculate energy deposition, neutron fluence, tritium breeding ratio, and super-conducting magnet radiation effects.[2] We used a 41 neutron group, 26 gamma group library with cross-section data based on the ENDF/B-V evaluation. We used P_3Legendre expansion order and S_8 angular quadrature. We were interested in the neutron energy multiplication factor, the total nuclear heating of cold (4.2 K) structure and magnets, and staying below radiation and heating limits.[3] The limits are:

1. S/C magnet neutron fluence = 10^{19} n/cm^2 (E > 0.1 MeV),
2. S/C magnet peak volumetric heating = 2 mW/cm^3,
3. S/C magnet polyamide insulation radiation = 10^{11} Rad, and
4. first wall neutron energy fluence = 16.4 MW-yr/m^2 which corresponds to 200 dpa in the first wall structure.

We are currently using a design safety factor of 3 to account for locally higher levels of heating and fluences.

System model:

Figure 1 shows the reference case blanket, shield, and magnet model.[3] (Modifications for a cauldron blanket are discussed in a later section of this paper.) Table 1 shows the associated material compositions with atomic densities. Table 2 shows the volume percents of materials within each zone.[3]

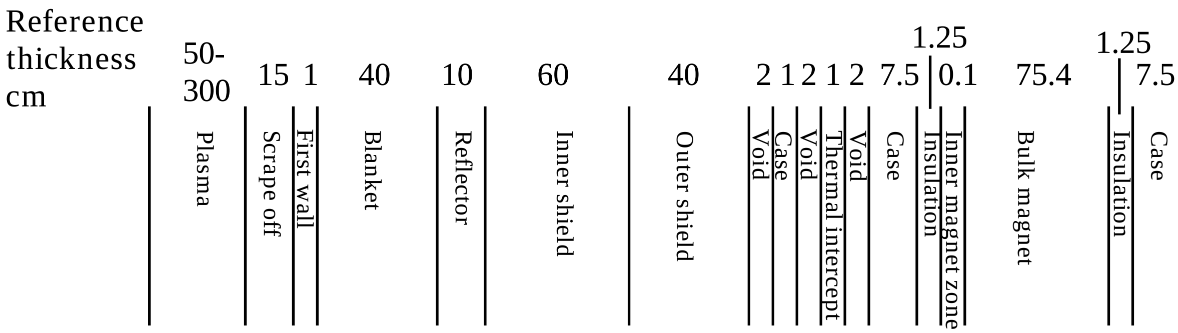

Figure 1. Reference case blanket, shield, and magnet model.

Table 1. Material compositions.

Material Name	**Component**	**Atom density $10^{22}/cm^3$**
Incoloy	Fe	3.556
	Ni	4.078
	Cr	.352
	Nb	.155
	Ti	.107
	Al	.186
	Si	.024
	Mn	.004
	C	.004
Liquid helium	He	2.108
Nb_3Sn	Nb	4.046
	Sn	1.3486
Tin	Sn	2.92
Vanadium	V	7.046
Copper	Cu	8.434
Aluminum	Al	6.03
Polyamide	Si	0.8765
	O-16	2.898
	Al	0.3966
	Mg	0.2
	C	2.12
	H-1	1.746
	N	0.35
Liquid nitrogen	N	3.474
Tenelon	Fe	6.0
	Mn	1.314
	Cr	1.39
	Si	0.0343
	C	0.06
Lithium	Li-6	0.316
	Li-7	3.954
Vanadium alloy	V	6.384
	Cr	0.347
	Ti	0.377
Borated tenelon	Fe	5.57
	Mn	1.314
	Cr	1.39
	Si	0.0343
	C	0.06
	B-10	0.257
	B-11	1.04

Table 2. Zone compositions

Model zone	**Material**	**Volume percent**
Magnet case	Incoloy	97
	Liquid helium	3
Insulation	Polyamide	100
Magnet	Incoloy	25
	Copper	27.32
	Nb_3Sn	3.42
	Tin	2.37
	Vanadium	1.89
	Liquid helium	15
	Polyamide	25
Thermal intercept	Aluminum	70
	Liquid nitrogen	20
First wall	Lithium	71.4
	Vanadium alloy	28.6
Blanket	Lithium	90
	Vanadium alloy	10
Reflector	Vanadium alloy	15
	Lithium	10
	Tenelon	75
Inner shield	Vanadium alloy	15
	Lithium	5
	Tenelon	80
Outer shield	Tenelon	15
	Borated tenelon	80
	Lithium	5

Method and results:

1-D coupled neutron-gamma transport calculations were performed to determine the effects of varying first wall radius, and blanket, inner shield, and outer shield thicknesses for cylindrical and spherical geometries applicable to the FRC and spheromak respectively. Calculations were normalized to 1 MW/m^2 first wall neutron load, and 30 full power years of operation. Appendix 1 shows typical data collected on each run. Tables 3 and 4 show selected data for cylindrical and spherical geometries respectively. We did inner shield variations for the cylindrical symmetry only. Only one zone width is modified at a time with the rest held to the reference width's shown in Figure 1. The reference cylindrical first wall radius is 115 cm and the reference spherical first wall radius is 315 cm.

Tables 3 and 4 use the following terminology. "Width" is the width of the zone being varied, "4.2 K heat" is the nuclear heating of the magnet and structure that must be maintained at 4.2 K, "Neutron fluence" is the inner magnet zone neutron fluence (E > 0.1 MeV), "Rad dose" is the inner magnet zone dose, "Local 4.2 K" is the inner magnet zone heating rate per unit volume, "TBR" is the tritium breeding ratio, and "M" is the neutron energy multiplication factor.

Table 3. Cylindrical geometry selected variational data.
Neutron wall load = 1MW/m^2. Lifetime = 30 full power years.

Width (cm)	**4.2 K heat (W/cm)**	**Neutron fluence (E_n > 0.1 MeV) n/cm^2**	**Rad dose (Rad)**	**Local 4.2 K (W/cm^3)**	**TBR**	**M**
Blanket						
25	0.57	1.68×10^{17}	2.74×10^{8}	1.70×10^{-5}	0.99	1.45
40	0.32	8.9×10^{16}	1.46×10^{8}	9.08×10^{-6}	1.21	1.38
55	0.18	4.64×10^{16}	7.69×10^{7}	4.80×10^{-6}	1.36	1.32
Inner shield						
40	2.96	1.03×10^{18}	1.50×10^{9}	9.06×10^{-5}	1.21	1.38
50	0.982	3.05×10^{17}	4.75×10^{8}	2.91×10^{-5}	1.21	1.38
60	0.32	8.9×10^{16}	1.46×10^{8}	9.08×10^{-6}	1.21	1.38
Outer shield						
20	4.81	1.59×10^{18}	2.41×10^{9}	1.47×10^{-4}	1.21	1.38
30	1.26	3.81×10^{17}	6.00×10^{8}	3.72×10^{-5}	1.21	1.38
40	0.32	8.90×10^{16}	1.46×10^{8}	9.08×10^{-6}	1.21	1.38
50	0.078	2.02×10^{16}	3.46×10^{7}	2.15×10^{-6}	1.21	1.38
First wall						
65	5.04 W / MW	6.89×10^{16}	1.14×10^{8}	7.07×10^{-6}	1.19	1.39
115	4.45 W / MW	8.9×10^{16}	1.46×10^{8}	9.08×10^{-6}	1.21	1.38

Table 4. Spherical geometry selected variational data.
Neutron wall load = 1MW/m^2. Lifetime = 30 full power years.

Width (cm)	**4.2 K heat (W)**	**Neutron fluence ($E_n > 0.1$ MeV) n/cm^2**	**Rad dose (Rad)**	**Local 4.2 K (W/cm^3)**	**TBR**	**M**
Blanket						
25	1148	2.11×10^{17}	3.36×10^{8}	2.09×10^{-5}	0.95	1.46
40	660	1.12×10^{17}	1.82×10^{8}	1.13×10^{-5}	1.18	1.40
55	375	5.91×10^{16}	9.66×10^{7}	6.02×10^{-6}	1.34	1.33
Outer shield						
20	9792	2.01×10^{18}	2.99×10^{9}	1.82×10^{-4}	1.18	1.40
30	2585	4.81×10^{17}	7.47×10^{8}	4.62×10^{-5}	1.18	1.40
40	660	1.12×10^{17}	1.82×10^{8}	1.13×10^{-5}	1.18	1.40
First Wall						
165	6.49 W / MW	7.92×10^{16}	1.29×10^{8}	8.01×10^{-6}	1.15	1.41
315	5.3 W / MW	1.12×10^{17}	1.82×10^{8}	1.13×10^{-5}	1.18	1.40

We can make some rather expected general statements regarding the data in Tables 3 and 4. Increasing blanket thickness increases the tritium breeding ratio and decreases the energy multiplication factor. The decrease in energy multiplication factor is probably due to an endothermic n-2n reaction with ^{7}Li. Increasing the thickness of any shielding material, reduces magnet radiation and heating. Changing the blanket thickness has less effect on shielding than changing the inner shield thickness which has less effect than changing the outer shield thickness. An increased first wall radius significantly reduces the effectiveness of a given thickness of shielding due to $1/r$ or $1/r^2$ geometrical effects. However, for a given shielding thickness, the shielding mass per unit first wall area is much larger for smaller first wall radii.

Tables 5 and 6 show the results of least squares fits of the data in Tables 3 and 4. We used exponential fits where appropriate, and linear fits elsewhere. These fits are approximately correct over the range of data from which they were taken for reference values of data except for the one that is being varied. They are also expected to give approximate values when used to calculate the effect of changing several thicknesses at once.

Table 5. Cylindrical Geometry: Least squares fits for varying zone thicknesses. Neutron wall load = 1MW/m². Lifetime = 30 full power years.

Blanket thickness x_b (cm)	
Energy multiplication factor	$1.55 - 0.0043x_b$
Tritium breeding ratio	$0.693 + 0.0123x_b$
4.2 K heat (W/cm)	$1.48 \exp(-0.0384x_b)$
Magnet neutron fluence (n/cm^2)	$4.92\times10^{17} \exp(-0.0429x_b)$
Magnet radiation dose (Rad)	$7.91\times10^{8} \exp(-0.04235x_b)$
Inner magnet zone heating (W/cm^3)	$4.88\times10^{-5} \exp(-0.04215x_b)$
Inner shield thickness x_i(cm)	
4.2 K heat (W/cm)	$254 \exp(-0.11123x_i)$
Magnet neutron fluence (n/cm^2)	$1.38\times10^{20} \exp(-0.11648x_i)$
Magnet radiation dose (Rad)	$1.59\times10^{11} \exp(-0.11502x_i)$
Inner magnet zone heating (W/cm^3)	$9.06\times10^{-3} \exp(-0.11502x_i)$
Outer shield thickness x_o (cm)	
4.2 K heat (W/cm)	$76.35 \exp(-0.1374x_o)$
Magnet neutron fluence (n/cm^2)	$2.96\times10^{19} \exp(-0.1455x_o)$
Magnet radiation dose (Rad)	$4.13\times10^{10} \exp(-0.1414x_o)$
Inner magnet zone heating (W/cm^3)	$2.50\times10^{-3} \exp(-0.1408x_o)$
First wall radius r_w (cm)	
4.2 K heat (W/MW)	$5.81 - 0.0118r_w$
Magnet neutron fluence (n/cm^2)	$(4.28 + 0.0402r_w)\times10^{16}$
Magnet radiation dose (Rad)	$(7.24 + 0.064r_w)\times10^{7}$
Inner magnet zone heating (W/cm^3)	$(4.46 + 0.0402)\times10^{-6}$

Table 6. Spherical Geometry: Least squares fits for varying zone thicknesses. Neutron wall load = 1MW/m^2. Lifetime = 30 full power years.

Blanket thickness x_b (cm)	
Energy multiplication factor	$1.57 - 0.00433x_b$
Tritium breeding ratio	$0.637 + 0.013x_b$
4.2 K heat (W)	$2922 \exp(-0.0373x_b)$
Magnet neutron fluence (n/cm^2)	$6.09\times10^{17} \exp(-0.04242x_b)$
Magnet radiation dose (Rad)	$9.53\times10^{8} \exp(-0.04155x_b)$
Inner magnet zone heating (W/cm^3)	$5.91\times10^{-5} \exp(-0.04149x_b)$
Outer shield thickness x_o (cm)	
4.2 K heat (W)	$1.46\times10^{5} \exp(-0.1348x_o)$
Magnet neutron fluence (n/cm^2)	$3.62\times10^{19} \exp(-0.1444x_o)$
Magnet radiation dose (Rad)	$4.93\times10^{10} \exp(-0.1400x_o)$
Inner magnet zone heating (W/cm^3)	$2.95\times10^{-3} \exp(-0.1390x_o)$
First wall radius r_w (cm)	
4.2 K heat (W/MW)	$7.8 - 0.00793r_w$
Magnet neutron fluence (n/cm^2)	$(4.31 + 0.02187r_w)\times10^{16}$
Magnet radiation dose (Rad)	$(7.07 + 0.03533r_w)\times10^{7}$
Inner magnet zone heating (W/cm^3)	$(4.39 + 0.02193r_w)\times10^{-6}$

Use of dpa data:

The first wall fluence limit of 16.4 MW years corresponds to approximately 200 dpa in the vanadium structure.[3] We obtained information on the displacements per atom (dpa) of copper that would occur for a given neutron fluence based on displacement cross sections for copper. We did not have this information for vanadium. Copper dpa is reduced roughly by a factor of 2 by 20 cm of blanket material. Although the actual cross-sections for displacements in vanadium will vary from those in copper, we extrapolate the results for and expect that blanket vanadium material 20 cm into the blanket would experience about half the number of dpa's, last about twice as long as first wall material, and only have to be replaced about half as often. Calculations using proper vanadium dpa cross-sections should be done verify this conclusion.

Example:

Suppose we desired to calculate the inner magnet zone neutron fluence (ϕ) that would occur in a power plant with the following parameters.

Geometry	Cylindrical
First wall radius	95 cm
Neutron wall load (P_n)	4 MW/m^2
Full power operation	30 years
Blanket thickness	35 cm
Inner shield thickness	50 cm
Outer shield thickness	30 cm

We will use the base equation from table 5 for the first wall radius, modified with differences from the reference case for the neutron wall load, and blanket, inner shield, and outer shield thicknesses.

$$\begin{aligned}
\phi &= \frac{P_n}{P_{no}}\left(4.28+\lambda_w r_w\right)\times 10^{16}\ \mathrm{n\ /\ cm^2}\exp\left(-\lambda_b \Delta x_b\right)\exp\left(-\lambda_i \Delta x_i\right)\exp\left(-\lambda_o \Delta x_o\right)\\
&= \frac{4}{1}\left(4.28+0.0402\times 95\right)\times 10^{16}\ \mathrm{n\ /\ cm^2}\exp\left(-0.0429\times\left(35-40\right)\right)\\
&\quad \exp\left(-0.11648\times\left(50-60\right)\right)\exp\left(-0.1455\times\left(30-40\right)\right)\\
&= 4\times 8.099\times 10^{16}\ \mathrm{n\ /\ cm^2}\times 1.24\times 3.21\times 4.28\\
&= 5.52\times 10^{18}\ \mathrm{n\ /\ cm^2}.
\end{aligned}$$

How much thicker would the outer shield have to be to allow a design safety factor of 3 below the fluence limit of 10^{19} n/cm^2?

$$\phi = \phi_o \exp\left(-\lambda \Delta x\right) \Rightarrow$$

$$\Delta x = \frac{\ln\left(\phi_o / \phi\right)}{\lambda} = \frac{\ln\left(5.52 / 3.33\right)}{0.1455\ /\ \mathrm{cm}} = 3.47\ \mathrm{cm}$$

for a total outer shield thickness of 33.5 cm.

Cauldron blanket:

A cauldron blanket similar to reference 4 was also considered for use as a spheromak blanket. The blanket consists of 50 weight percent each of molten sodium and lithium. We assume a 3 m radius plasma with a 15 cm scrape-off layer. The reference case first wall, blanket, inner shield, and outer shield thicknesses are changed to 4 cm, 150 cm, 30 cm, and 20 cm respectively. The other material thickness are as shown in Figure 1. The lithium in the first wall, reflector, and shield are replaced by equal volume percents of sodium.

We used ONEDANT to perform neutronics calculations for the assumed spherical symmetry. Again we calculated the effects of varying blanket and inner shield thicknesses for spherical geometry. Calculations were normalized to 1 MW/m^2 first wall neutron load, and 30 MW years of operation. Table 7 shows selected data from the ONEDANT calculations. Only one zone width is modified at a time with the rest held to the reference width's. Tables 8 shows the results of least squares fits of the data in table 7.

We also did a comparison calculation with a 67 weight percent sodium 33 weight percent lithium blanket. The shielding characteristics were nearly the same, but the tritium breeding ratio dropped from 1.36 to 1.18. This may be a more desirable blanket mixture since it is the sodium that we are vaporizing for heat transfer purposes.

Table 7. Spherical Geometry:
Cauldron blanket selected variational data.

Width (cm)	**4.2 K heat (W)**	**Neutron fluence n/cm^2**	**Rad dose (Rad)**	**Local 4.2 K (W/cm^3)**	**TBR**	**M**
Blanket						
130	17635	3.48×10^{18}	4.39×10^{9}	2.54×10^{-4}	1.33	1.21
150	9229	1.99×10^{18}	2.12×10^{9}	1.23×10^{-4}	1.36	1.20
Inner shield						
30	9229	1.99×10^{18}	2.12×10^{9}	1.23×10^{-4}	1.36	1.20
50	1242	1.72×10^{17}	2.54×10^{8}	1.55×10^{-5}	1.36	1.20

Table 8. Spherical Geometry:
Least squares fits for varying cauldron zone thicknesses.

Blanket thickness x_b (cm)	
4.2 K heat (W)	$1.19\times10^{6}\exp(-0.03238x_b)$
Magnet neutron fluence (n/cm^2)	$1.32\times10^{20}\exp(-0.02794x_b)$
Magnet radiation dose (Rad)	$4.98\times10^{11}\exp(-0.03634x_b)$
Inner magnet heating (W/cm^3)	$2.83\times10^{-2}\exp(-0.03626x_b)$
Inner Shield thickness x_i (cm)	
4.2 K heat (W)	$1.87\times10^{5}\exp(-0.1003x_i)$
Magnet neutron fluence (n/cm^2)	$7.83\times10^{19}\exp(-0.1224x_i)$
Magnet radiation dose (Rad)	$5.11\times10^{10}\exp(-0.1061x_i)$
Inner magnet heating (W/cm^3)	$2.75\times10^{-3}\exp(-0.1036x_i)$

Summary:

We set up reference case 1-D blanket, shield, and magnet models for fusion power plants. We used the ONEDANT neutronics code to calculate heating, tritium breeding ratio, neutron energy multiplication factor, inner magnet neutron fluence, and radiation dose for reference case zone thicknesses and variations from the reference case. We calculated linear and exponential fits to the data which can be used to calculate neutronics information for a wide range of first wall radii and blanket and shield thicknesses. This neutronics information, along with radiation limits, can be used in systems studies to help calculate appropriate sizes for Li-V, or cauldron blankets and shields for fusion energy power plants.

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Acknowledgements:

We wish to thank Laila El-Guebaly from the University of Wisconsin for help in getting started with the FRC blanket calculations. She suggested a starting composition and dimensions for the blanket and gave us radiation and heating limits. She later provided us with an example input file for the ONEDANT neutronics code and answered several questions we had regarding its use. We also wish to thank Hosny Ahaya of Argonne National Laboratory for his help in interpreting nuclear data files. This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

		Reference case cylindrical geometry spreasdsheet							
zone name	Plasma	Scrape off	First wall	Blanket	Reflector	Inner Shield	Outer Shiel	Void	
width	100	15	1	40	10	60	40	2	
outer radiu	100	115	116	156	166	226	266	268	
fine mesh	10	3	1	20	5	30	20	1	
tot fine me	10	13	14	34	39	69	89	90	
	Case	Void	Liquid Nitroge	Void		Case	Insulation	Inner magnet	
	1	2	1	2		7.5	1.25	0.1	
	269	271	272	274		281.5	282.75	282.85	
	1	1	1	1		4	1	1	
	91	92	93	94		98	99	100	
	Magnet	Innsulation	Case		normalization	3.18E+16			
	75.4	1.25	7.5		tritium	3.84E+16		material	density g/cm3
	358.25	359.5	367		TBR	1.207547		incloy	8.071833
	20	1	4		Energy Multip	1.375796		lhe	0.13944
	120	121	125		DPA first wall	311		nb3sn	8.9806
			Mag n fluence	8.90E+16	DPA cen blank	125		sn	5.7487792
		LOCAL HEATING			DPA out blank	61.4		v.	5.956827
Component	Radius	Heat ev/cm	Heat W/cm3					cu	8.886063
								al	2.702646
in blanket	117	2.01E+19	3.216					poly	1.9675482
cen blanke	135	1.10E+19	1.76					ln	0.8134
out blanket	155	6.99E+18	1.1184					tenlon	7.98070564
in reflector	157	1.51E+19	2.416					l i	0.4904636
out reflect	165	7.98E+18	1.2768					v	5.9924008
								b-tenlon	7.8140848

		ZONE HEATING					
Component	volume	Heat ev/cm	Heat W/cm	Heat W/cm3	Density g/cm3	Heat W/g	Rads(30 MW-yr/m2)
first wall	7.26E+02	1.72E+22	2752	3.79063361	2.06401764	1.836532	1.74E+14
blanket	3.42E+04	3.86E+23	61760	1.80584795	1.04065732	1.735295	1.64E+14
reflector	1.01E+04	1.13E+23	18080	1.79009901	6.93343571	0.258184	2.44E+13
in shield	7.39E+04	1.04E+23	16640	0.22516915	7.30794781	0.030812	2.91E+12
out shield	6.18E+04	3.99E+20	63.84	0.00103301	7.47289687	0.000138	1.31E+10
mag case	1.31E+04	9.50E+17	0.152	1.1603E-05	7.83386121	1.48E-06	1.4E+08
insulation	2.22E+03	4.22E+16	0.006752	3.0414E-06	1.9675482	1.55E-06	1.46E+08
inner magn	1.78E+02	1.01E+16	0.001616	9.0787E-06	5.51440033	1.65E-06	1.56E+08
bulk magne	1.52E+05	9.98E+17	0.15968	1.0505E-06	5.51440033	1.91E-07	18021867
total		6.21E+23	99360				
Cold heating			0.320048				

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